Applying Predictive Maintenance to Power Quality

Application Note

The purpose of this applicaion note is to explain how predictive maintenance can be used to prevent and therefore avoid power problems in electrical distribution systems. Predictive maintenance techniques have long been employed to prevent loss of operation in mechanical equipment such as engines, and in electromechanical equipment, such as motors. By analyzing the frequency spectrum of vibration in bearings, for example, and comparing how the frequency spectrum changes over time, it is possible to provide early warning of impending failures. The motor can be scheduled for maintenance and the weak bearing replaced. Similar early warning of incipient problems in an electrical distribution system can also be achieved.

Power is a raw material

Industries and businesses of all types are constantly seeking ways to improve their quality and productivity to remain competitive and profitable. It is standard practice to measure the quality of raw materials. Electrical power is not often thought of as a raw material, but it is vital to virtually all types of manufacturing. The quality of power is therefore of concern; for example power disruptions in a semiconductor fabrication plant can result in millions of dollars of lost production. Semiconductor manufacturers go to great lengths and expense to ensure the quality of one particular raw material, water, and continually monitor its purity. The purity of water is just one of many indices of quality that is tracked in a manufacturing industry. It is now possible to monitor similar metrics for power.

Unlike many raw materials power is consumed as soon as it is generated. It cannot be stored to be analyzed for quality in the future. If power quality is unsatisfactory it cannot be recycled or repaired and returned to the process. It must be monitored continuously and its quality established in "real-time". The continuous monitoring of power is becoming more widely adopted. Monitoring systems are often installed to determine the amount and cost of energy consumed, but for many industries the cost of power disruption can outweigh energy costs. Power quality and harmonics should be monitored along with consumption. To meet these needs, a new generation of monitors is available that comprehensively monitors all aspects of power, and plays an important role in total quality management.

Benefits of continuous monitoring

In many government, military, financial, and commercial "mission critical" applications, computers run 24 hours a day, 365 days a year. These vital computers may be performing diverse tasks such as air traffic control or processing millions of dollars in transactions. Consequently, owners and operators of these systems go to great lengths to prevent disruption or downtime. They have made significant investments in their infrastructures to ensure the reliability of power delivery. Every major data center possesses large UPS and back-up generator systems, with carefully laid out conduit and power distribution. Their goal is a simple one, to achieve 100 % "up time" or system availability. The cost of comprehensive power monitoring instruments has dropped by over 50 % during the last few years, making it economically feasible to continuously monitor power quality at multiple locations on distribution systems.

Continuous monitoring of the power delivery infrastructure should be an integral part of any proactive management program. It provides many benefits, some of which are:

- Continuous monitoring provides the data to perform a post mortem on disruptive power disturbance incidents. This data is needed to determine how and where events were caused, leading to an understanding of how they may be avoided in the future, and how the effects may be mitigated.
- Harmonics must be monitored on a continuous basis to ensure that, over time, the incremental addition of loads does not cause excessive heating that can lead to the premature failure of transformers, conductors and circuit breakers.
- Continuous tracking of power consumption and RMS quantities provide useful data for planning future plant expansion and for ensuring existing and future utility feeder and substation capacities are adequate. It is also useful for planning the addition of new discrete loads or new back-up power systems. A comprehensive view of the power system is critical in plants that schedule maintenance shut-downs once or twice per year. Long term data from multiple nodes can insure that appropriate work is performed during the short maintenance window.

- Archiving power survey reports containing all aspects of power in great detail in a database provides the ability to compare existing conditions with historical conditions and to predict when a failure will occur. This concept is called "Predictive Maintenance." Predictive techniques provide the information required to achieving 100% "up time."
- Key personnel can be alerted immediately when a power problem is detected by issuing alarms or by sending messages to pagers or PC screens. Immediate notification allows action to be taken to isolate a problem and prevent a domino effect that would jeopardize the entire facility.

Utilities can also reap benefits from continuous monitoring. Several utilities are deploying power-monitoring instruments at all levels of generation and distribution systems to improve operational efficiencies. They are also instituting pro-active power quality monitoring programs to benefit their customers, either as part of a power delivery contract or to increase good-will. In some cases they make the data available to end-users so they can incorporate power quality information into their operational planning. Ethernet can link several monitors installed at service entrances and key locations on the customer's premises. When many instruments are scattered over several remote sites, the utility can also rely on telephone and modem communications.

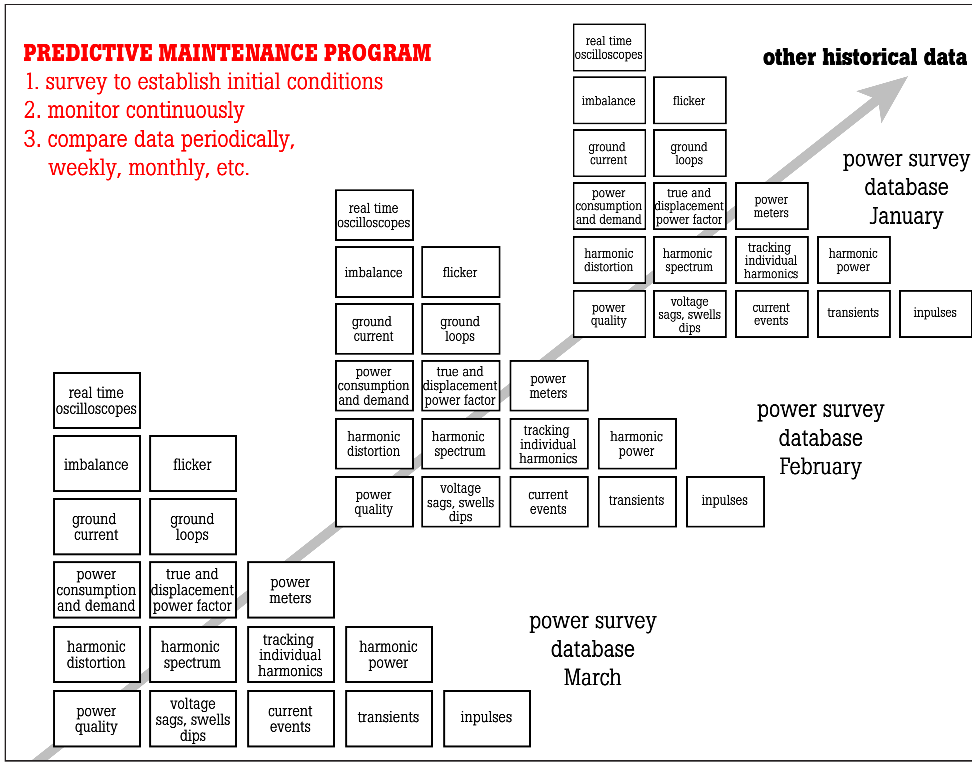

Figure 1. Predictive maintenance by periodic comparison of historical data.

Comparing historical data

The idea of trending data over time to perform predictive maintenance is not new. If we can spot an undesirable trend emerging, we can take action to arrest it. This philosophy has been successfully used in performing predictive maintenance in other fields. By measuring regularly vibration on bearings and comparing the vibration frequencies over time the early stages of a bearing failure can be detected. The motor or machine can then be scheduled for a bearing replacement. Similar predictive techniques, can be applied to track the deterioration of an electrical infrastructure.

A predictive maintenance program can be established by installing monitors at critical locations. Each monitor performs a survey for a reasonable "business-period" such as a week or a month. When a survey is finished the data is downloaded and saved, and the monitor is automatically reset to perform another survey for another week or month. Each survey database is archived, and the databases are compared periodically, (figure 1). Multiple databases collected over long periods of time provide engineers with a comprehensive power history of a plant's power system utility infrastructure. By continuously tracking the changes in the power situation and comparing events on a weekly or monthly basis conditions that are or deteriorating will be highlighted.

It is important to perform an initial survey to establish the true baseline conditions and provide the basis for comparing to subsequent survey data. It is also important that each subsequent database is a faithful record of the true condition of the power system. This requires a "full disclosure" power monitoring technology. Full disclosure monitors capture power consumption, harmonics, and power quality information in great breadth and depth without requiring the user to program triggers or thresholds.

Setting limits and thresholds eliminates vast areas of the power tolerance curve creating a "dead zone" as shown in figure 2. Older technology monitors that

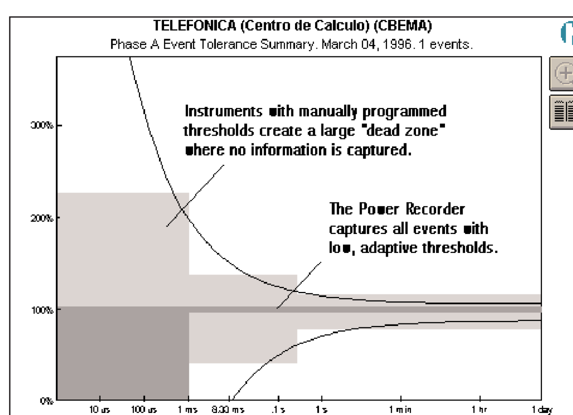

Figure 2. Dead zone eliminates potentially valuable data.

use triggers or set-points collect no information in this zone. It is not possible to establish the true baseline conditions since there is no information about events are occurring below the thresholds. Without this information we will not be aware of a deteriorating power situation until trigger values are exceeded; not until it is too late. Full disclosure monitors capture not only the severe events but also the latent data that may indicate incipient problems.

Breadth and depth of full disclosure technology

Full disclosure monitors make many simultaneous measurements:

- **Power Consumption:** e.g., Watts, VA, VAR, PF (true and displacement), demand, and KWH.
- **Voltage Events:**
  Voltage transients: between 0.5 microseconds and 8 milliseconds (half a cycle).
  Voltage disturbances: between half a cycle and 2 seconds (typically wave shape changes and brief RMS events).
  RMS voltage events greater than 2 seconds: typically sags, swells, outages, etc.
  Voltage imbalance.
  Flicker: periodic voltage fluctuations less than 25 Hz as defined by IEC 868.
  Ground loops: Current in a non-current carrying conductor; often a problem in large networked systems, usually caused by the interconnection of multiple peripherals or communications equipment to processors.
- **Harmonic Distortion:** harmonic spectra for voltage and current for all conductors, THD (Total Harmonic Distortion). Tracking of individual voltage and current harmonics.

The detail and the accuracy of power consumption and harmonics measurements depend not only on sampling rates, but also on processing power. Full disclosure monitors use high-speed digital signal processors that measure RMS, as well as all other electrical parameters, on every cycle. Many power monitors for example, use low-speed sampling and do not have the processing power or storage to calculate all the necessary measurements. Recording is continuous with a RPM full disclosure monitor so nothing is missed and accuracy is enhanced.

Turning data into information

The objective of complete power reliability can be measured in terms of availability or uptime. How then to prevent disruption and damage and get advance warning of an impending problem? Power monitors collect large volumes of data but it is not useful in its raw form. It must be analyzed to provide information so that that the operators can develop an understanding of the state of their power infrastructure. Converting data to information leads to knowledge. Armed with knowledge action can be taken; practical plans, procedures and solutions can be implemented. Software tools have been developed to gather and manage the vast amount of data from multiple monitors performing power surveys. These tools contain many novel features that allow users to interpret power monitor information and present it in a variety of ways in order to gain insight and reach informed conclusions.

Power Quality Index

Traditionally power quality monitors have been used for performing post-mortems of power quality problems, such as a computer or electronic equipment malfunction. The data may be inconclusive if no events were recorded during the monitoring session (with older monitors this situation is worrisome since the user may be unsure whether the monitor was set up incorrectly or whether no events actually occurred). If the monitor collects a large amount of data it becomes difficult to make sense

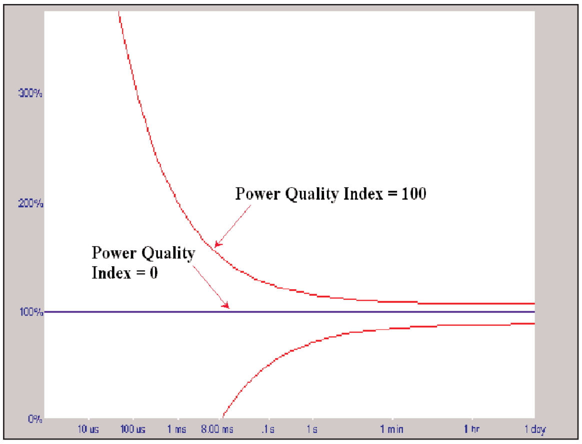

Figure 3. Power quality index calculation.

of all the sags, swells, transients, harmonics and consumption data. The sheer mass of data becomes overwhelming. With all the data that is collected it is impossible for users to answer the simple question of whether their power is getting worse or getting better, and to predict if they will experience a serious disruption in the future. New software to analyze the data from full disclosure monitors can now answer these questions to help attain the goal of reliability.

One technique is to convert the power quality data into an index that can be tracked over time. A scheme to develop a simple, single number index is shown in figure 3. As each event is recorded it is given an index depending upon its relationship to a power quality tolerance curve such as the CBEMA curve or the ITIC curve (recently proposed as the new CBEMA curve). If an event lands on the curve it is given an index of 100. An event (or rather no event) that shows no deviation from the nominal voltage is given an index of zero. If an event is halfway between nominal and the curve it is given an index of 50, if it is twice the distance from nominal as it is from the curve it is given an index of 200, and so on.

Figure 4 shows the RMS value of the power quality index plots for four power monitors installed at four locations. Index plots show when the power quality is deteriorating (index goes up) and when power quality is improving (index goes down) or if the power quality is fluctuating. In this example, the index for the monitor installed in the Network Closet shows the most stable power situation, while the index for the Lobby monitor is going up at the fastest rate and is fluctuating to a greater extent than the other monitors do. By comparing the index plots to each other it becomes apparent which points have better or worse power quality than others. If the Lobby location were a critical one, this scheme indicates it is the worst of the four locations and is worthy of investigation first. If the index is allowed to continue to accelerate this location will inevitably suffer some undesirable consequence. If action is taken at a particular location and a solution is implemented the index should stabilize and go down. Indexing quickly and intuitively provides confirmation that the power quality situation is improving.

An advantage of linking the index to power quality curves is that if the curve doesn't exactly describe the sensitivity to power quality at a given location the curve can be edited or re-shaped to influence the index. The CBEMA curve is a general curve and in some situations the user's equipment or location may be more sensitive to impulses or high-speed transients, for example. The curve could be adjusted to become more sensitive in the microsecond region. This has the effect of giving greater weight to the index in the impulse.

Often the exact shape of the curve that describes the operational limits or the sensitivity of electronic equipment may not be known. By logging and noting which events cause equipment problems the user can develop a specific curve from empirical data and recalculate the index. Since all past survey data is in a database it can be re-indexed at any time simply by editing the curve.

Manipulating the data

The software provides tools to allow the user to delve further into the data that makes up the index. These tools offer great flexibility by allowing the user to compare and trend any parameter against any other parameter, as well as tools to compare the data at one location with another location, or one survey to another. Figure 5 shows the plot of the RMS value of the power quality index for the Service Entrance monitor along with the maximum index of the worst case event. Figure 6 is a composite plot of the power quality index and RMS voltage activity and shows a correlation between power failures and the index. Certain index values have significance. For example, power failures have indices near 1000 since the distance to 0% voltage from nominal voltage compared to the distance to the curve from nominal is about ten to one. If the index does not correlate with the RMS activity, a high index value most likely correlates with an impulse or transient. Figure 7 shows the event history plotted against the RMS voltage history, the + symbols indicate when an event was recorded. Correlation between events and RMS activity can be seen, if events do not fall on the RMS plot, i.e. they are in the upper portion of the graph above the RMS plot, they are transient or impulse events. Clicking on an event will display a RMS sag or swell plot or a transient waveform.

Figure 4. Power quality index plots at 4 locations.

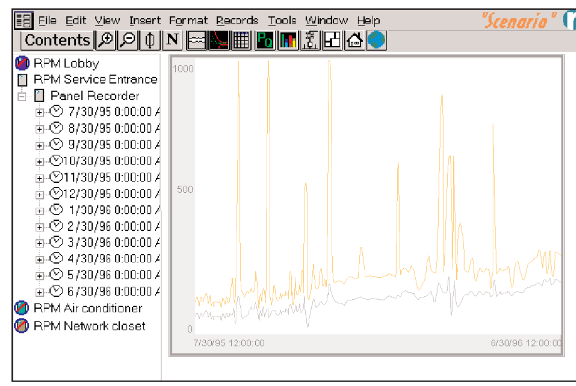

Figure 5. Power quality index, RMS and maximum.

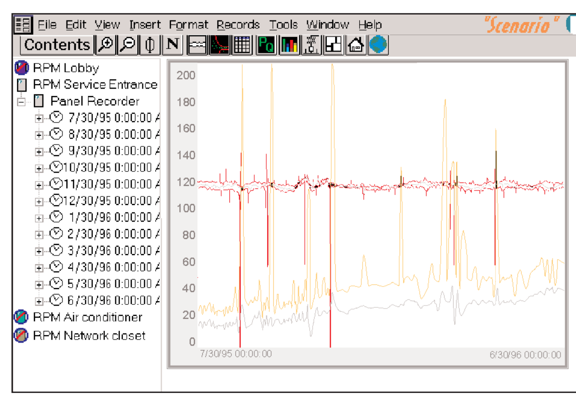

Figure 6. Index and RMS voltage superimposed.

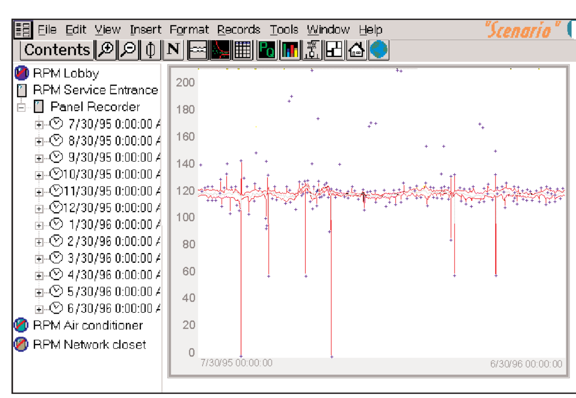

Figure 7. RMS voltage superimposed with event history.

Highlighting trends

Following the progress of the index is one method of highlighting deterioration or improvement in power quality. Another approach is to use a power tolerance curve and shade the events according to age, figure 8. Oldest events are shaded darkest and recent events are shaded the brightest. The shading makes it easy to see if events are getting worse or better. In this example there is a "migration" effect in the seconds region showing that sags are steadily becoming worse over time. Clouds of events whose perimeters are brighter than the inside indicates a region where problems are expanding. If the center of a cloud of events is brighter problems are consolidating in one area. In figure 8 there are two groups of impulses in the microsecond region. Both impulse groups indicate that impulses have been getting worse over time and the most recent events in the upper group now border on the curve indicating action should be taken. The fact that the impulses got worse over time is significant. Two scenarios come to mind. One is that new loads have been added which are creating switching transients. The current or consumption profiles for the past several months could be inspected to support this theory, equipment installation and operation logs may indicate changes, additions, or repairs. A physical inspection may be called for to see whether new loads have been added without our knowledge. The other explanation is that the transient suppression systems may not be functioning correctly; perhaps the MOV's or other elements have aged or failed and need to be replaced. This is a good example of how a full disclosure monitoring system provides early warning. With threshold-type monitors the user would not be aware of the deterioration in the system until voltage variations eventually grow to the point where they exceed the threshold limits and are captured, but by this time damage to sensitive equipment will have already occurred.

Viewing across multiple sites and databases

The ability to easily compare data across multiple monitors at multiple locations is useful for correlating power disturbances on one circuit with activity on other circuits to understand their relative effects and influences. This is useful for utilities monitoring several substations or multiple feeders, as well as industrial facilities monitoring several key points around their operation. Figure 9 shows a composite power tolerance curve displaying all the events from monitors at four sites. Events for each monitor are color-coded. The software allows the user to select how much or little data may be presented by turning the databases on or off with software buttons. By toggling between databases and turning colors on or off the user could compare events from one location in a certain region of the curve with events in the same region for another monitoring location. This technique helps users quickly see which events at a facility's service entrance have any effect on locations further inside the operation, for example. Another useful display for correlating events across multiple locations plots multiple monitors' disturbance events in a 3-D display, figure 10.

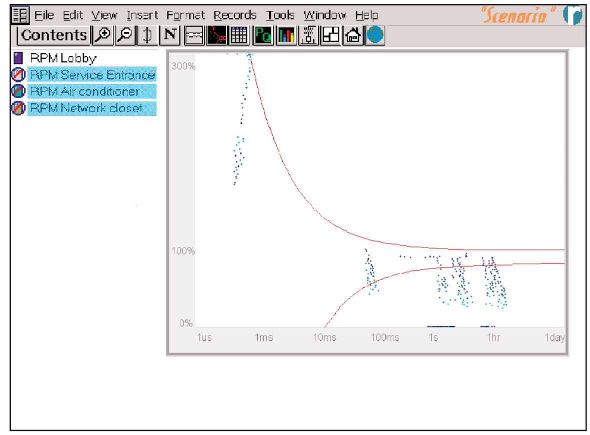

Figure 8. Power tolerance curve with shaded events.

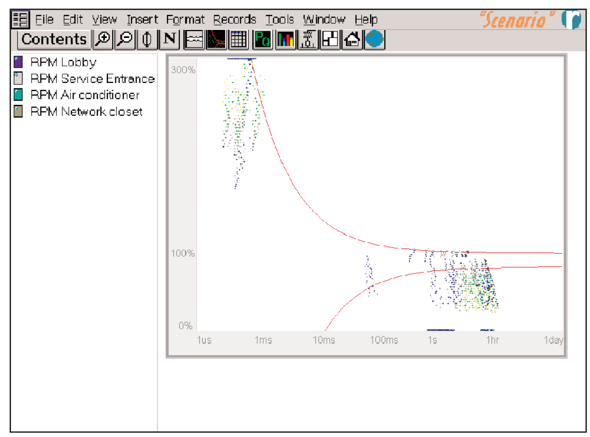

Figure 9. Comparing multiple locations.

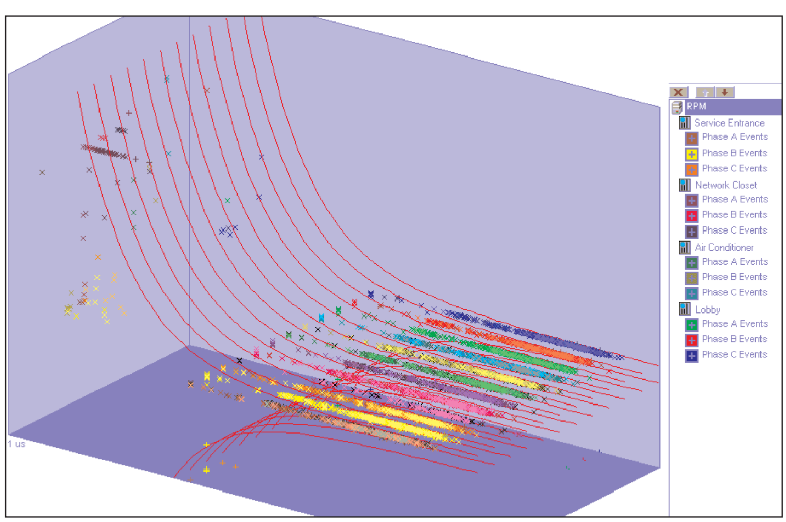

Figure 10. 3-D plot.

Portable monitors can perform predictive maintenance

The greatest benefits of predictive maintenance are realized with a network of permanently installed monitors, but portable trouble-shooting instruments can also be used in predictive maintenance programs providing they are the full disclosure types. One approach would be to take a monitor to a location where power quality is of concern (at an adjustable speed drive, or at a computer controlled device, or at the output of an UPS) and monitor for a reasonable period (24 or 48 hours) and archive the monitoring data. The monitor can be moved on to several other locations to perform more surveys and subsequent survey data is also archived. After a month we return to our first location and make another survey. By repeating this over several weeks or months, several power survey databases will have been archived. They are imported into the predictive maintenance software and the index is plotted for each location. There will be gaps in the plots since monitoring was not continuous, but the index will still indicate whether the power is improving or deteriorating, figure 11. If equipment problems develop, consulting the index would lead us to include (or eliminate) power quality as a cause before investigating hardware or software bugs.

Conclusion

New "full disclosure" monitors capture all aspects of power in great detail in a single instrument. These new instruments can be used either as portable instruments or as permanently installed monitors, figure 12. Full disclosure technology eliminates the need for the user to program thresholds or triggers. They automatically capture significant events and manage monitor memory with low, adaptive thresholds. Instruments that require manually programmed triggers are prone to incorrect set-up and are blind to conditions that are "bubbling under" the threshold limits. Only full disclosure instruments can capture all the necessary information to perform predictive maintenance, and they consistently capture and analyze data the same way every time they are used.

A full disclosure monitoring system can establish the true baseline conditions of the entire power system and provide the basis for comparison on a weekly or monthly basis. A new predictive science for electrical systems will evolve and (especially in the era of utility deregulation) we will see the creation of consulting and analysis services aimed at the goal of increased reliability in industrial, utility and commercial applications. Many businesses already perform some predictive maintenance in their operations, but now they have the opportunity to extend predictive-monitoring programs to of their power delivery systems and infrastructures.

For more information contact us at 1-800-443-5853 or at info-sales@fluke.com

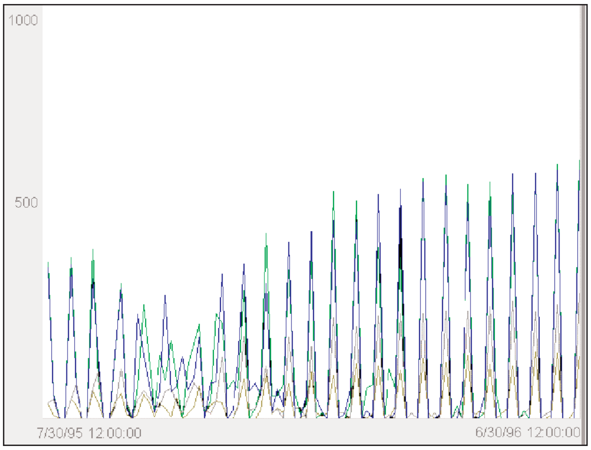

Figure 11. Plotting PQ index from portable monitors.


Figure 12. Permanently installed full disclosure power monitor.

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